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Original article

The fluid–solid coupling analysis of screw conveyor in drilling fluid centrifuge based on ANSYS

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ABSTRACT

In the centrifugal separations of drilling fluid, screw conveyor is a critical component to push and separate the sediment. The work performance and structural parameters of conveyor are immediately related to the production capability, the working life and the separating effect of the centrifuge. The existing researches always use the theoretical calculation of the approximate loads to analyze the strength of conveyor, and it cannot reflect the stress situations accurately. In order to ensure the precise mastery of the working performance, this article obtained pressure distribution under working conditions from CFX evaluation and gained equivalent stress and deformation under several load conditions by using the ANSYS Workbench platform to check the strength of conveyor. The results showed that the influence of centrifugal hydraulic pressure was less than that of centrifugal force on the strength and deformation of conveyor. Besides, the maximum equivalent stress occurred at the inside of the feed opening, while the maximum deformation occurred at the conveyor blade edge of taper extremity. Furthermore, whether considered the feed opening or not, the computing model had a great influence on the analysis results, and the simplified loads had a great influence on the deformation analysis results. The methods and results from this article can provide reference for the design and the improvement of screw conveyor.

1. Introduction

As a solid control equipment, drilling fluid centrifuge plays an important role in drilling operations [1]. Researchers paid more attention to the research of centrifuge constantly, including the flow state of particle suspension, the optimization of operating conditions of the decanter centrifuges, and the structure improvement [2]. G.R.A. Bell et al. [3] developed a mathematical model to calculate the power and torque required for product transport by the scroll in a decanter centrifuge. G.R. Zhu et al. [4] applied FLUENT software to an M-2301-type horizontal screw decanter centrifuge to simulate the fluid flow situation in the centrifuge drum and obtain the solid concentration distribution. S.F. Zheng et al. [5] analyzed pressure distribution and velocity distribution used by the RSM and DPM model in FLUENT software. P. Yu [6] and J.G. Liu [7] et al. used the DPM model in FLUENT software to simulate the relationship between the centrifugal field velocity and structure parameters. S.C. Fu [8] and L.D. Dong [9] et al. used the RNG k–ε model to simulate the velocity distribution and pressure distribution in decanter centrifuge. A.J. Liu et al. [10] used Visual Nastran to make static analysis and modal analysis of horizontal decanter centrifuge conveyor. Y. Tao et al. [11] analyzed the stress state of conveyor under several load conditions by using Pro/E. L.Q. Wang et al. [12] used ANSYS to build parameterized finite element model, and researched influence of blade thickness and cone half angle on rotor's structure strength and inherent characteristics. Z. Yang et al. [13] used SolidWorks to make static analysis and modal analysis of conveyor with large ratio of length to diameter, and researched the influence of lead, rotational speed, blade thickness and other parameters on conveyor's stress and deformation.

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Conveyor was a key part to transport the sediment continuously, the structural reliability of conveyor made a great impact on safety working of the whole unit, therefore, researchers paid more attention to the strength calculation and structural optimization of conveyor. In these studies, the flow field or static structure was calculated, however, they didn't contact each other, approximate loads of conveyor was used in the model's analysis and calculation, and it was computed by theoretical calculation. This method greatly simplified the flow pressure, so the stress of conveyor was estimated roughly. The stress distribution on conveyor and the exact location of the maximum stress were not obtained. Furthermore, the effects of feed nozzles on stress and deformation were not taken into consideration. Therefore, further studies are needed to obtain the real stress and deformation of conveyor.

In order to avoid the error that approximates the centrifugal hydraulic pressure to positive pressure and frictional force, and compute conveyor's strength and deformation in flow field exactly, this article used one-way fluid–solid coupling method to evaluate the conveyor system. Conveyor's pressure loads were obtained through the flow field numerical calculation about drilling fluid centrifuge, and then stress and deformation distribution of conveyor was gained by finite element analysis. The calculation methods and results from this article can provide reference to conveyor's design and improvement.

2. Fluid-structure coupling problem solving method

Fluid-structure interaction (FSI) mechanics is a branch of mechanics, generating from mutual cross effect between hydrodynamics and solid mechanics. This subject mainly studies the behaviors of solid in the flow field and the influence of deformation or movement on the flow field. The problem solving strategies of FSI are strong coupling [14], weak coupling [15] or one-way coupling [16]. Compared to the size of flow field in centrifuge, the deformation of conveyor blade was tiny, so one-way coupling method was used, and the impact of solid deformation was ignored. First, the section of flow field was solved. Second, the flow pressure of solved flow section was transferred to structure, and then combined with the coupling interface information to solve the structural elements.

2.1. Fluid equations

Typically, conservation laws of fluid flow consist of mass conservation, momentum conservation, and energy conservation. Generally, centrifuge interior fluid flow does not consider the energy transfer, and it can be described by mass conservation equation and energy conservation [17] as follows:

Mass conservation equation:

$$\frac{\partial \rho_f}{\partial t} + \nabla \cdot \left(\rho_f v\right) = 0 \tag{1}$$

Momentum conservation equation:

$$\frac{\partial \rho_f v}{\partial t} + \nabla \cdot \left(\rho_f v v - \tau_f\right) = f_f \tag{2}$$

where t is the time, f_f is the volume force vector, ρ_f is the fluid density, v is the fluid speed vector, τ_f is the tensor of shearing force, expressed as:

$$\tau_f = (-p + \mu \nabla \cdot v) I + 2\mu e$$

where p is the fluid pressure, μ is the dynamic viscosity, e is the tensor of speed stress, $e = 1/2(\nabla v + \nabla v^T)$.

2.2. Structural equations

The conservation of structure can be derived from Newton's second law:

$$\rho_s \ddot{d}_s = \nabla \cdot \sigma_s + f_s \tag{3}$$

where ρ_s is the structural density, σ_s is the Cauchy's stress tensor, f_s is the volume force vector, $\ddot{d}_s$ is the structural local acceleration vector.

2.3. Fluid-structure coupling equations

At the interface, the fluid-structure coupling which does not consider thermal conduction should satisfy that liquid displacement (d_f) and structure displacement (d_s) are equal. Furthermore, the conservation of liquid stress (τ_f) and structure stress (τ_f) should be satisfied.

$$\begin{cases} d_f = d_s \\ \tau_f \cdot n_f = \tau_s \cdot n_s \end{cases} \tag{4}$$

where n_f, n_s are the normal direction of τ_f, τ_s.

3. Fluid-structure coupling models

3.1. Calculation models building

A LW450-1000 drilling fluid centrifuge was used to calculate. The main parameters of the centrifuge are listed in Table 1.

The geometry of flow field and structure field were all built in Pro/E and meshed by the pre-processing software ICEM CFD. The model was complicated, thus the unstructured tetrahedral mesh was used. The conveyor structure was meshed with a total of 683,605 cells and 125,473 nodes. The flow field was meshed with a total of 797,365 cells and 138,509 nodes. The flow field and structure field models are shown in Figs. 1 and 2 respectively.

3.2. Boundary conditions

3.2.1. Fluid flow boundary conditions

The inlet boundary was defined as velocity inlet, the processing capacity was 60 m^3/h, so the inlet velocity was 2.95 m/s. The solid–liquid two-phase flow model was used, and water-based drilling fluid of non-aggravated was selected for calculation. The properties of water-based drilling fluid are listed in Table 2.

Table 1
Structure parameters for the LW450-1000 drilling fluid centrifuge.

Parameter	Value
Drum inner radius	225 mm
Cylinder inner radius	152 mm
Scroll pitch	108 mm
Taper angle	8°
Spiral angle	7.59°
Length of conical section	418 mm
Length of cylindrical section	582 mm

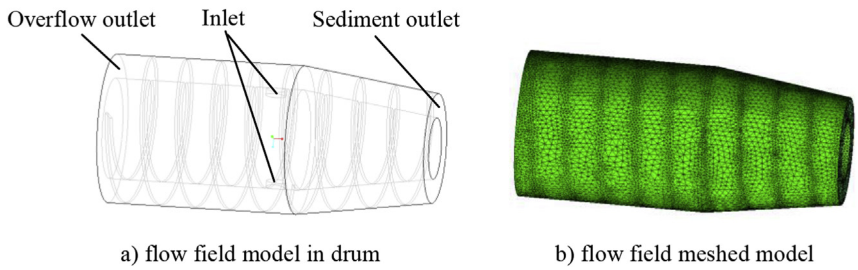


Fig. 1. Flow field model in drum.

3.2.2. Loads and boundary conditions of structure field [18]

When working with stability, the loads of screw conveyor include:

(1) Centrifugal force generated by high-speed rotation. Centrifugal load applied in the form of angular velocity. The angular velocity ω is calculated as:

$$\omega = \frac{2\pi \cdot \mathrm{n}}{60} = \frac{2 \times 3.14 \times 3000}{60} = 314\ \mathrm{rad/s} \tag{5}$$

where n is the rotating speed of screw conveyor, in this article, n = 3000 r/min.

(2) Coriolis force. When study on the characteristics of rotary motion, in addition to the centrifugal force, the Coriolis force may arise. According to theoretical mechanics, when the implicated movement is a fixed axis of rotation at constant angular speed, size of Coriolis acceleration is:

$$\alpha_k = 2\omega V_r \tag{6}$$

where V_r is the radial velocity of particle relative to drum.

Coriolis force is defined as:

$$F_k = 2m\omega V_r \tag{7}$$

Theoretically, the Coriolis force in a centrifuge does exist, but it is always ignored in general engineering problems, because of its weak influence and relatively complex mathematical operation.

(3) Centrifugal hydraulic pressure. When the centrifuge is on working, the liquid and sediment layer will exert considerable pressure to the inner wall of drum under the action of centrifugal force, which is called centrifugal hydraulic pressure. The calculation formula of centrifugal hydraulic is shown as follows:

$$p_c = \rho\omega^2 \int_{r_1}^{R} r dr = \frac{1}{2}\rho\omega^2\left(R^2 - r_1^2\right) \tag{8}$$

where p_c is the hydraulic pressure, ρ is the density of material, ω is the rotating velocity of drum, R is the radius of drum, r is the inner radius of drum.

In the calculation of Refs. [10–13], they were all calculated through approximating the centrifugal hydraulic pressure to positive pressure and friction on the screw conveyor, and then exerted combination loads on the model to calculate by applying the linear elastic superposition principle. It exerted pressure by coupling the flow field and structure field and loaded the hydraulic pressure from flow calculation to the structure domain. Therefore, there were two major loads applied on the model: inertial load and surface load, the former was the rotating velocity of screw conveyor, and the latter was the hydraulic pressure applied on the fluid-structure coupling interface, which was obtained by the flow field calculate.

By the design of horizontal decanter centrifuge, both ends of screw conveyor were supported by bearing on both sides of the inner drum respectively. Therefore, one end of the solid model subjected full constraint, the other end was restricted by displacement of Y and Z directions. Model constraints imposed are shown in Fig. 3.

4. Results of the simulation

In order to investigate the effect on screw conveyor by centrifugal force and hydraulic pressure, the model was calculated at three load situations respectively to get the stress and deformation of conveyor. The loads were centrifugal force, centrifugal hydraulic pressure, and the combination. The equivalent stress and deformation of each load are shown in Figs. 4–6.

By the static analysis of the screw conveyor under various kinds of loads, the maximum equivalent stress was 67.772 MPa under the action of centrifugal force, and it occurred at the inside of the feed opening. The maximum equivalent stress was

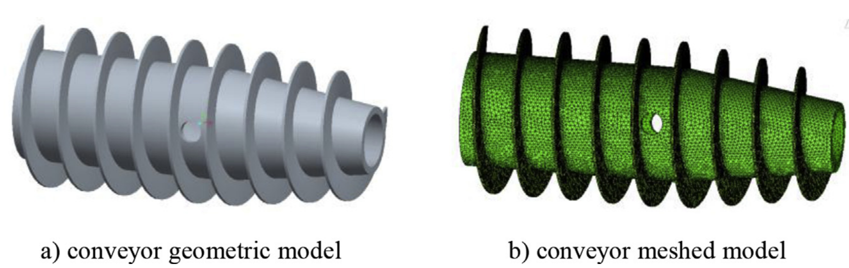


Fig. 2. Screw conveyor model.

Table 2
Physical properties for the water-based drilling fluid.

Sample	Value
Liquid density	1000 kg/m^3
Solid density	2030 kg/m^3
Solid average diameter	50 μm
Suspension viscosity	0.0217 Pa s
Suspension volume fraction	30%

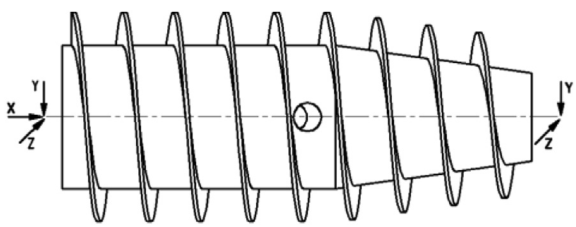


Fig. 3. Constraints of screw conveyor.

19.156 MPa under the action of centrifugal hydraulic pressure, and it occurred at the root of the screw blades of the conic section. The maximum equivalent stress was 86.575 MPa under the action of combination loads. With the allowable design stress 207 MPa, the maximum stress of conveyor was less than the allowable design stress, and the conveyor was secure with enough strength.

In Refs. [10–13], when the feed opening was not taken into consideration, the strength analysis of conveyor showed that the maximum stress occurred at the root of screw blades of the cylinder. In the analysis of this article, the maximum equivalent stress occurred at the inside of the feed opening, and the reason was that the feed opening is the location where the feeding pipe and the screw conveyor are welded. Due to the sudden change of the structure, the stress concentration was generated, so welding procedure should be paid great attention and the influence of weld seam should be considered for local strengthening. The simulation results also showed that the feeding opening has a great effect on force analysis of the model.

In addition to the stress concentration of the feed opening, the comparatively large stress of conveyor occurred at the cylinder and the screw blades root of the cylinder with the uniform distribution. According to the simulation results, the equivalent stress ranged from 19 MPa to 38 MP, which demonstrated the stress situation of screw blades was fine and indicated no possible danger. It was substantially different from the results in the reference. The result illustrated that the predigestion of loads has a great effect on the stress of the screw blades. Actually, the stress of screw blades is uniform.

The maximum deformation under centrifugal force occurred at the screw blades edge of taper extremity. The maximum deformation under centrifugal hydraulic pressure occurred at the edge of the working face of the screw blades on the conic section. The maximum deformation under combination loads occurred at the edge of working face of the screw blades on the end of the conic section with the maximum deformation 0.0499 mm. The results of Fig. 5 revealed that the influence of deformation generated by centrifugal force was more than by centrifugal hydraulic pressure.

In Ref. [12], the maximum deformation occurred at the outer edge of the cylinder screw blades. The results in this article

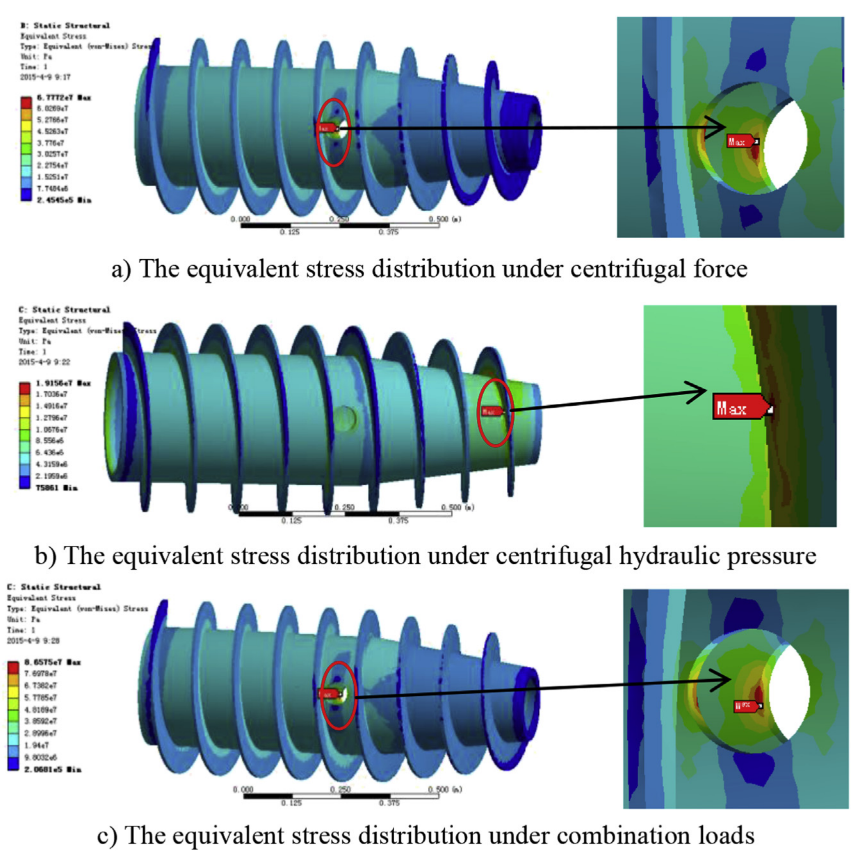
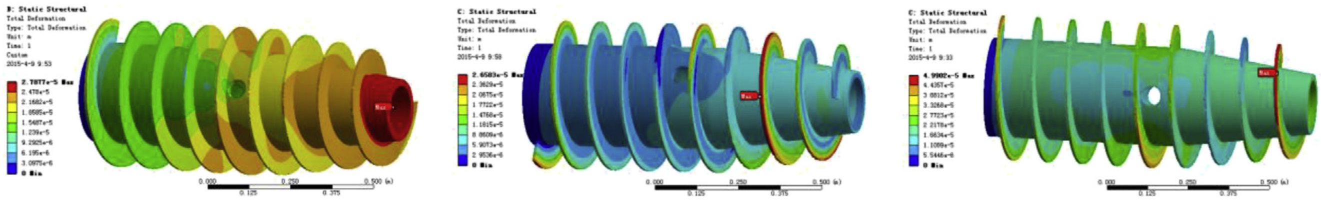
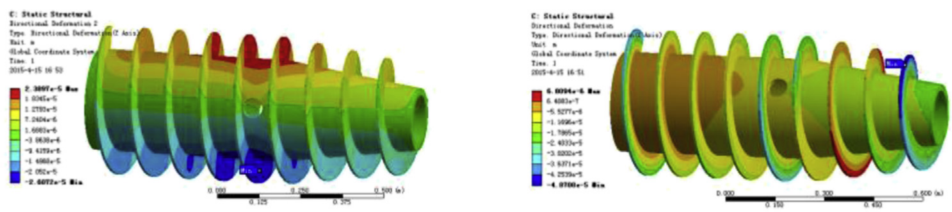


Fig. 4. The equivalent stress distribution under each kinds of load.



a) Under centrifugal force b) Under centrifugal hydraulic pressure c) Under combination loads

Fig. 5. Deformation distribution under each kinds of load.



a) Radical deformation under combination loads b) Axial deformation under combination loads

Fig. 6. The radical deformation and axial deformation under combination loads.

were quite different from that in Ref. [12], because the pressure of conveyor was loaded by the FSI method and the pressure was not distributed uniformly, while in Ref. [12], the load was simplified and uniformly applied to the conic section of screw blades. It showed that simplifying loads has a great effect on the analysis of deformation of the screw conveyor. And it was essential to get the real pressure loads by the fluid-structure coupling method.

The maximum radical deformation of conveyor was 0.0261 mm, which occurred at the working face of the screw blades on cylinder. It was much less than 0.8 mm, which is the smallest gap between the screw conveyor and the drum. Furthermore, the maximum axial deformation of the conveyor was 0.0487 mm, which was so minimal that cannot have an effect on normal working of conveyor. So, the stiffness of conveyor also met the requirements.

5. Conclusions

By applying the ANSYS Workbench platform, the structural strength of drilling fluid centrifuge conveyor was analyzed based on fluid-structure coupling simulation. The following conclusions can be drawn from this work:

(1) The maximum stress of screw conveyor under centrifugal hydraulic pressure was 19.156 MPa, and the maximum stress under centrifugal force was 67.772 MPa, which showed that centrifugal force had a greater effect on the structural strength of conveyor compared with the centrifugal hydraulic pressure. The maximum rotational speed of conveyor should be paid attention both in design and in service.

(2) Under the action of fluid-structure coupling, the maximum stress of conveyor was 86.575 MPa, which met the requirements of strength. The maximum stress occurred at the inside of the feed opening. This result was different from that in the reference which the maximum stress occurred at the root of screw blades of the cylinder. The results showed that considering the feed opening or not had a great effect on strength analysis of the screw conveyor.

(3) The maximum stress occurred at the inside of the feed opening whether it's under the centrifugal force or under the combination loads, because the feed opening was the location where the feeding pipe was welded. Due to the sudden change of the structure, the stress concentration was generated. Therefore, the welding technology and local reinforcement should be considered during welding.

(4) The maximum deformation of conveyor was 0.0499 mm under the action of fluid-structure coupling, occurring at the edge of the working face of the screw blades on the end of the conic section, which was different from that in reference. The result showed that simplifying load has a great effect on the analysis of the deformation of screw conveyor. So, it's necessary to get the pressure loads on the real work condition by the fluid-structure coupling method.

(5) It's the first time to analyze the strength of screw conveyor by using the fluid-structure coupling method. Compared with the analysis of the static load based on theoretical calculation of approximate pressure, the pressure loads from fluid-structure coupling are more accuracy. The calculation methods and results from this article can serve as a reference for the design and improvement of screw conveyor.

Acknowledgments

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References

[1] COSL, Drilling Solids Control Technical Manual, Southwest Jiaotong University Press, 2011.
[2] W. Tan, L. Qiao, E.D. Sha, L.Y. Liu, Optimal design of the accelerator disk in a two-stage piston pusher centrifuge using numerical simulation, Ind. Eng. Chem. Res. 51 (12) (2012) 4632–4642.
[3] G.R.A. Bell, D.D. Symons, J.R. Pearse, Mathematical model for solids transport power in decanter centrifuge, Chem. Eng. Sci. 107 (7) (2014) 114–122.

[4] G.R. Zhu, W. Tan, Y. Yu, L.Y. Liu, Experimental and numerical study of the solid concentration distribution in a horizontal screw decanter centrifuge, Ind. Eng. Res. 52 (48) (2013) 17249–17256.
[5] S.F. Zheng, X. Ren, L.J. Xie, Numerical simulation of flow field in decanter centrifuge, Light Ind. Mach. 27 (6) (2009) 26–29.
[6] P. Yu, W. Lin, X.L. Wang, et al., Velocity simulation analysis on centrifugal separation field of horizontal spiral centrifuge, J. Mech. Eng. 47 (24) (2011) 151–157.
[7] J.G. Liu, Numerical Simulation and Drum Angle Research on Flow Field of Centrifuges, Jilin University, 2011.
[8] S.C. Fu, L.D. Dong, H.X. Yuan, Numerical simulation and analysis on flow field in a decanter centrifuge based on the Euler model, Chem. Ind. Eng. Pro. 33 (1) (2014) 36–42.
[9] L.D. Dong, S.C. Fu, H.X. Yuan, Numerical simulation on pressure field in a decanter centrifuge, Chem. Ind. Eng. Pro. 33 (2) (2014) 309–313, 336.
[10] A.J. Liu, C.M. Fu, Static finite element screw conveyor to a horizontal centrifuge analysis, J. Des. Res. 34 (3) (2007) 26–28.
[11] Y. Tao, Z.J. Ai, J.P. Wang, et al., 3D finite element analysis of drilling fluid centrifuge conveyor, Oil Field Equip. 37 (11) (2008) 69–72.
[12] L.Q. Wang, T. Chen, D.Z. Wu, et al., Structural strength parameterized analysis of horizontal decanter centrifuge conveyor, J. Mach. Des. 27 (5) (2010) 67–70.
[13] Z. Yang, W.J. Huang, Z.H. Gao, et al., Finite element analysis of horizontal decanter centrifuge screw with large length-diameter ratio, J. Filtr. Sep. 04 (2011) 13–19.
[14] J. Yang, S. Preidikman, E. Balaras, A strongly coupled, embedded-boundary method for fluid-structure interactions of elastically mounted rigid bodies, J. Field Struct. 24 (2) (2008) 167–182.
[15] Y.Y. Jiang, I.S.R. Yoshimura, et al., Quantitative evaluation of flow-induced structural vibration and noise in turbo machinery by full-scale weakly coupled simulation, J. Field Struct. 23 (4) (2007) 531–544.
[16] ANSYS Inc, ANSYS CFX, Release 12.0, ANSYS Inc, USA, 2009.
[17] X.G. Song, L. Cai, H. Zhang, et al., ANSYS Fluid-structure Coupling Simulation and Engineering Design, China Water Conservancy and Hydropower Press, 2012.
[18] Q.C. Sun, D.W. Jin, Centrifuge Principle Structure and Design Calculations, Machinery Industry Press, 1987.